

Tracing the Universe with Clusters of Galaxies

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Abstract

Clusters of galaxies, the most massive virialized systems known, provide a powerful tool for studying the structure, the mass density, and the cosmology of our universe. Clusters furnish one of the best estimates of the dynamical mass density parameter on 1 Mpc scale, Ω_{dyn} ; the best measure of the baryon density fraction in the universe; an excellent tracer of the large-scale structure of the universe; and, most recently, a powerful tracer of the evolution of structure in the universe and its unique cosmological implications. I review the above measures and show that they portray a consistent picture of the universe and place stringent constraints on cosmology. Each of these independent measures suggests a low-density universe, $\Omega_m \simeq 0.3 \pm 0.1$, with mass approximately tracing light on large scales.

1. Cluster Masses and Ω_m

Masses of clusters of galaxies can be determined (within a given radius) from three independent methods: 1) in the optical, from velocity dispersion of galaxies in the clusters, assuming hydrostatic equilibrium (e.g., Zwicky, 1957, Bahcall, 1977, Peebles 1980, Carlberg, et al., 1996); 2) in X-rays, from the temperature of the hot intracluster gas (e.g., Jones and Forman, 1984, Sarazin, 1986, Hughes, 1989, Evrard, et al., 1996); and 3) from lensing, using weak gravitational lens distortions of background galaxies caused by the intervening cluster mass (e.g., Tyson, et al., 1990, Kaiser and Squire, 1993, Smail, et al., 1995, Kneib, this volume). All three independent methods yield consistent results for the mass of rich clusters (typically measured within $R \simeq 0.5 - 1.5h^{-1} \text{ Mpc}$); (e.g., Lubin and Bahcall 1993, Bahcall 1995, Fischer and Tyson 1997, Hjorth, et al., this volume, and references therein). The rms scatter in the mass determination among the different methods is typically $\sim \pm 30\%$, with no significant bias. The observed consistency among the different methods ensures that we can reliably determine cluster masses, within the observed scatter. The masses of rich clusters range from $\sim 10^{14}$ to $\sim 10^{15}h^{-1}M_\odot$ within $1.5h^{-1} \text{ Mpc}$ radius of the cluster center. When normalized by the cluster luminosity, a median value of $M/L_B \simeq 300 \pm 100h$ is observed for rich clusters, independent of the cluster luminosity, velocity dispersion, or other parameters. (Here L_B is the total blue luminosity of the cluster, corrected for internal and Galactic absorption). (See also Carlberg, et al., this volume, for detailed results of the

CNOC cluster survey.) This mass-to-light ratio, when integrated over the luminosity density of the universe, yields a dynamical mass density of $\Omega_{dyn} \simeq 0.2$ on $\sim 1.5h^{-1} Mpc$ scale. This density assumes that all galaxies (and other large structures) exhibit the same high M/L_B ratio. If the mass distribution is not biased, i.e., if mass follows light on large scales, then a global $\Omega_m \simeq 0.2$ is implied for the cosmological density parameter. If, on the other hand, as desired by theoretical considerations, the universe has a critical density ($\Omega_m = 1$), then most of the mass of the universe has to be unassociated with galaxies (i.e., with light, even to these large scales of $\sim 1.5h^{-1} Mpc$), and reside, instead, mostly in the “voids” where there is no light. An $\Omega_m = 1$ universe thus requires a large bias in the distribution of mass versus light, with mass distributed considerably more diffusely than light.

Is there a strong bias in the universe, with most of the dark matter residing on large scales, well beyond galaxies and clusters? A recent analysis of the mass-to-light ratio of galaxies, groups and clusters (Bahcall, Lubin and Dorman, 1995) suggests a negative reply. The study shows that while the M/L ratio of galaxies increases with scale up to radii of $R \sim 0.1 - 0.2h^{-1} Mpc$, due to large dark halos around galaxies, this ratio appears to flatten and remain approximately constant for groups and rich clusters, to scales of $\sim 1.5 Mpc$, and possibly even to the larger scales of superclusters (Fig. 1). The flattening occurs at $M/L_B \simeq 200 - 300h$, corresponding to $\Omega_m \simeq 0.2$. This observation is contrary to the classical picture where the relative amount of dark matter is believed to increase with scale (possibly reaching $\Omega_m = 1$ on large scales). The present data suggest that most of the dark matter may be associated with the dark halos of galaxies and that clusters do not contain a substantial amount of additional dark matter, other than that associated with (or torn-off from) the galaxy halos, and the hot intracluster gas. This flattening of M/L with scale, if confirmed by further larger-scale observations, suggests that the relative amount of dark matter does not increase significantly with scale (above $\sim 0.2h^{-1} Mpc$); in that case, the mass density of the universe is low, $\Omega_m \simeq 0.2 - 0.3$, with no significant bias.

2. Baryons in Clusters

Clusters of galaxies contain many baryons, observed as gas and stars. Within $1.5h^{-1} Mpc$ of a rich cluster, the X-ray emitting gas contributes $\sim 3 - 10h^{-1.5}\%$ of the cluster virial mass (or $\sim 10 - 30\%$ for $h = \frac{1}{2}$ (Briel, et al., 1992, White and Fabian, 1995). Visible stars contribute another $\sim 5\%$. Standard Big-Bang nucleosynthesis limits the baryon density of the universe to $\Omega_b \simeq 0.015h^{-2}$ (Walker, et al., 1991). This suggests that the baryon fraction in rich clusters exceeds that of an $\Omega_m = 1$ universe by a factor of ~ 3 (White, et al., 1993, Lubin, et al., 1996). Detailed hydrodynamic simulations (above references) show that

baryons are not preferentially segregated into rich clusters. This implies that either the mean density of the universe is considerably smaller, by a factor of ~ 3 , than the critical density, or that the baryon density of the universe is much larger than predicted by nucleosynthesis. The observed baryonic mass fraction in rich clusters, combined with the nucleosynthesis limit (Walker, et al., 1991, Tytler, this volume), suggest $\Omega_m \simeq 0.2 - 0.3$; this estimate is consistent with $\Omega_{dyn} \simeq 0.2$ determined from cluster dynamics.

3. The Cluster Mass Function

The observed mass function (MF) of clusters of galaxies, $n(> M)$, describes the number density of clusters above a threshold mass M ; it serves as a critical test of theories of structure formation in the universe. The richest, most massive clusters are thought to form from rare high peaks in the initial mass-density fluctuations; poorer clusters and groups form from smaller, more common fluctuations. Bahcall and Cen (1993) determined the MF of clusters of galaxies using both optical and X-ray observations of clusters. They compared the observed mass function of galaxy clusters with predictions of N-body cosmological simulations (Bahcall and Cen 1992) for standard ($\Omega_m = 1$) and low-density ($\Omega_m < 1$; flat or open) Cold Dark Matter (CDM) models. They find that standard $\Omega_m = 1$ CDM models, with any normalization, can not reproduce well the observed cluster mass function. An $\Omega_m = 1$ model requires a low normalization, $\sigma_8 \simeq 0.5$ (where σ_8 is the rms mass fluctuation amplitude on $8h^{-1}Mpc$ scale), in order to fit the observed abundance of richness class $\gtrsim 1$ clusters. (A $\sigma_8 \simeq 1$ $\Omega_m \simeq 1$ model overproduces massive clusters by an order of magnitude.) This low σ_8 (high bias) model, however, is too steep at the most massive tail of the cluster MF. A low density ($\Omega_m \simeq 0.2 - 0.3$) CDM model, flat or open, with little or no bias, provides a good fit to the data.

The present-day cluster abundance (from the mass or temperature functions of clusters) places one of the strongest constraints on cosmology (see above; also White, et al., 1993, Eke, et al., 1996, Viana and Liddle, 1996, Pen, 1997); $\sigma_8 \Omega_8^{0.5} \simeq 0.5 \pm 0.05$ (with a small dependence on Λ). This constraint, while powerful, is degenerate in Ω_m and σ_8 ; it requires that models with $\Omega_m = 1$ have low normalization ($\sigma_8 \sim 0.5$), i.e., strongly biased models, with mass distributed considerably more diffusely than light, since $\sigma_8(gal) \simeq 1$ is observed for optical galaxies); models with $\Omega_m \simeq 0.25$ need to have a high normalization ($\sigma_8 \simeq 1$, comparable to optical galaxies, i.e., an unbiased universe with mass tracing light on large scales). (The cluster mass function of Bahcall and Cen, 1993 (see above) best fits the $\Omega_m \simeq 0.25$ unbiased models, especially at the high-mass end.) Standard $\Omega_m = 1$ CDM models with COBE normalization of $\sigma_8 \simeq 1$ are strongly ruled out by the observed present-day cluster

abundance; they produce too many massive clusters.

4. Evolution of the Cluster Abundance

The observed present-day abundance of rich clusters places one of the strongest constraints on cosmology (§4): $\sigma_8 \Omega_m^{0.5} \simeq 0.5 \pm 0.05$. This constraint is degenerate in Ω_m and σ_8 : models with $\Omega_m = 1$ and $\sigma_8 \simeq 0.5$ are indistinguishable from models with $\Omega_m \simeq 0.25$ and $\sigma_8 \simeq 1$ (Eke, et al. 1996; Pen 1997; Kitayama and Suto 1997). In a recent paper (Bahcall, Fan, and Cen 1997) we show that the *evolution* of the cluster abundance as a function of redshift breaks the degeneracy between Ω_m and σ_8 and determines each of the parameters independently (see also Carlberg, et al., this volume). The growth of high-mass clusters depends strongly on the cosmology – mainly σ_8 and Ω_m (e.g., Press and Schechter, 1974, Peebles, 1993, Cen and Ostriker, 1994, Jing and Fang, 1996, Eke, et al., 1996, Viana and Liddle, 1996, Oukbir and Blanchard, 1997). In low-density (high- σ_8) models, density fluctuations evolve and freeze out at early times, thus producing only little evolution at recent times ($z < 1$). In an $\Omega_m = 1$ universe, the fluctuations start growing more recently thereby producing strong evolution in recent times: a large increase in the abundance of massive clusters is expected from $z \simeq 1$ to $z \simeq 0$. The evolution is so strong that finding even a few Coma-like clusters at $z > 0.5$ over $\sim 10^3 \text{deg}^2$ of sky would contradict an $\Omega_m = 1$, $\sigma_8 \simeq 0.5$ model, where only $\sim 10^{-2}$ such clusters would be expected.

The evolution of the abundance of massive (Coma-like) clusters with mass M ($\leq R_{phy} = 1.5 h^{-1} \text{Mpc}$) $\geq 6.3 \times 10^{14} h^{-1} M_\odot$ is presented in Fig. 2 (from Bahcall, et al., 1997). The expected evolution is obtained from large-scale cosmological N-body simulations ($400 h^{-1} \text{Mpc}$ box size) for different cosmologies: Standard Cold Dark Matter (SCDM, $\Omega_m = 1$, COBE normalized: $\sigma_8 = 1.05$), SCDM with $\sigma_8 = 0.53$ (normalized to the present-day cluster abundance; §4), Mixed Dark Matter (MDM: hot + cold), Open CDM (OCDM, $\Omega_m = 0.35$, $\sigma_8 = 0.8$), and Lambda CDM (LCDM, $\Omega_m = 0.4$, $\Lambda = 0.6$, $\sigma_8 = 0.8$) (see Bahcall, et al., 1997 for details). Several effects are clearly seen in Fig. 2:

1. The evolution of the abundance of high-mass clusters breaks the degeneracy between Ω_m and σ_8 that exists at $z \simeq 0$;
2. Low - σ_8 models (high Ω_m) evolve much faster than high - σ_8 models (low Ω_m). The abundance of clusters with this mass decreases by a factor of $\sim 10^2$ from $z = 0$ to $z \simeq 0.5$ for biased ($\sigma_8 \simeq 0.5 - 0.6$) SCDM models, while the decrease is much shallower, only a factor of ~ 5 , for the $\Omega_m \simeq 0.3$ ($\sigma_8 \simeq 0.8$) models.

3. Even at reasonably nearby redshifts of $z \sim 0.5$, the difference in cluster abundance between high and low Ω_m models (low and high σ_8) is very high (factor of $\sim 10^2$) for these high mass clusters.
4. The available data, using the CNOC cluster survey (Carlberg, et al., 1997) and the distant EMSS survey (Luppino and Gioia, 1994), are consistent with the low-density models (OCDM, LCDM), and inconsistent with the biased $\Omega_m = 1$ CDM models (see Fig. 2, and Bahcall, et al., 1997). Too many high mass clusters are observed at $z \simeq 0.5 - 0.8$ to be consistent with $\Omega_m = 1$, $\sigma_8 \simeq 0.5$ models; these biased models predict a factor of $\sim 10^2$ less clusters than observed.

The mild observed evolution of cluster abundance places a powerful constraint on cosmology by breaking the degeneracy between Ω_m and σ_8 ; we find $\sigma_8 = 0.83 \pm 0.15$ and $\Omega_m \simeq 0.3 \pm 0.1$. (See also Carlberg, et al., this volume, for similar results). We present these constraints in Fig. 3.

Fan, Bahcall and Cen (1997) investigate the reason for the strong (exponential) dependence of the evolution rate on σ_8 ; they show that Ω_m is determined mostly from the *normalization* of the cluster abundance, while σ_8 is determined mostly from the *rate* of evolution. The exponential dependence of the evolution rate on σ_8 arises because clusters of a given mass represent rarer density peaks in low σ_8 models compared with high σ_8 models, thus evolving considerably faster in low σ_8 Gaussian models. The high σ_8 value required by the mild observed cluster evolution rate implies a bias parameter of $b \simeq \sigma_8^{-1} \simeq 1.2 \pm 0.2$, i.e., a nearly unbiased universe with mass approximately following light on large scale. The $\Omega_m \simeq 0.3 \pm 0.1$ constraint, obtained from the cluster abundance normalization for this σ_8 value, agrees well with the *independent* constraints placed by cluster dynamics and by the high baryon fraction observed in clusters (§2-3).

5. Clusters and Large-Scale Structure

Clusters of galaxies serve as excellent tracers of the large-scale structure of the universe. The strong cluster correlation function (Bahcall and Soneira 1983, Klypin and Kopylov 1983) was the first to reveal the common existence in the universe of large-scale structures to $\sim 50h^{-1}Mpc$ or more. The richness-dependence of the cluster correlation function (Bahcall and Soneira 1983, Bahcall and West 1992), is now observed for various samples of clusters (including the APM survey (Croft, et al., 1997), with consistent results and a weakening of the richness dependence at the richest cluster tail). The cluster correlation function has been used successfully in constraining cosmological models. The strong amplitude and

large-scale extent of the cluster correlations are inconsistent with $\Omega_m = 1$ CDM models, for any normalization; the correlations are in good agreement with low-density, $\Omega_m \sim 0.2 - 0.3$ CDM models (Bahcall and Cen 1992, Croft, et al., 1997). Other large-scale structure observations such as the power-spectrum (of galaxies and clusters), the galaxy correlation function, and the cluster peculiar motions, all suggest a low-density universe, with $\Omega_m h \sim 0.2$ (e.g., Maddox, et al., 1990, Peacock and Dodds 1992, Bahcall and Oh 1996, Croft, et al., 1997, Tadros, et al., 1997, Einasto, et al., 1997 and this volume, and Retzlaff, et al., 1997 and this volume). New large-scale surveys of galaxies and clusters, currently underway, will further improve the constraint placed on this parameter

6. Is $\Omega_m < 1$?

Much of the observational evidence from clusters and from large-scale structure suggests that the mass density of the universe is sub-critical: $\Omega_m \simeq 0.2 - 0.3$. I summarize these results below:

1. The masses and the M/L(R) relation of galaxies, groups, and clusters suggest $\Omega_m \simeq 0.2 - 0.3$ (§2).
2. The high baryon fraction in clusters of galaxies suggests $\Omega_m \simeq 0.2 - 0.3$ (§3).
3. Various observations of large-scale structure (the cluster mass function, the correlation function, the power spectrum, and the peculiar velocities on Mpc scale) all suggest $\Omega_m h \simeq 0.2$ (for a CDM-type spectrum (§ 4,6)).
4. The evolution of the cluster abundance to $z \simeq 0.5 - 1$ yields $\Omega_m \simeq 0.3 \pm 0.1$ (§5).
5. All the above independent observations suggest a low-density universe, $\Omega_m \simeq 0.3 \pm 0.1$.
6. If $H_0 \sim 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, as indicated by a number of recent observations, then the observed age of the oldest stars requires $\Omega_m \ll 1$.
7. Peculiar motions on large scales are too uncertain at the present time (suggesting density values that range from $\Omega_m \sim 0.2$ to ~ 1) to reliably constrain Ω_m . Future results, based on larger and more accurate surveys, will help constrain this parameter (see, e.g., Strauss and Willick, 1996; Dekel; Gramann; this volume).

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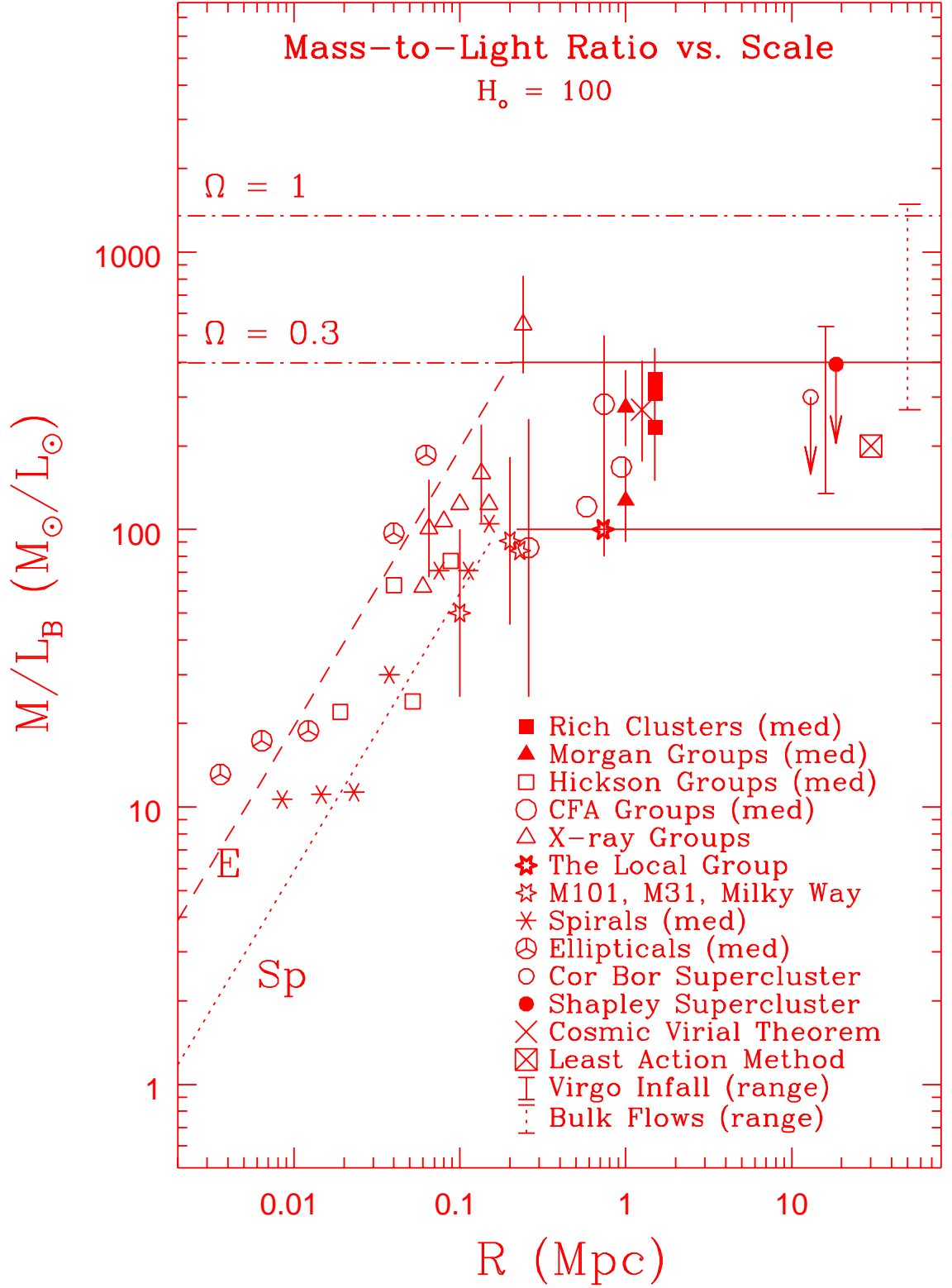


Fig. 1 The dependence of M/L on scale, R , for galaxies, groups, clusters, and larger-scale structures. From Bahcall, Lubin and Dorman (1995).

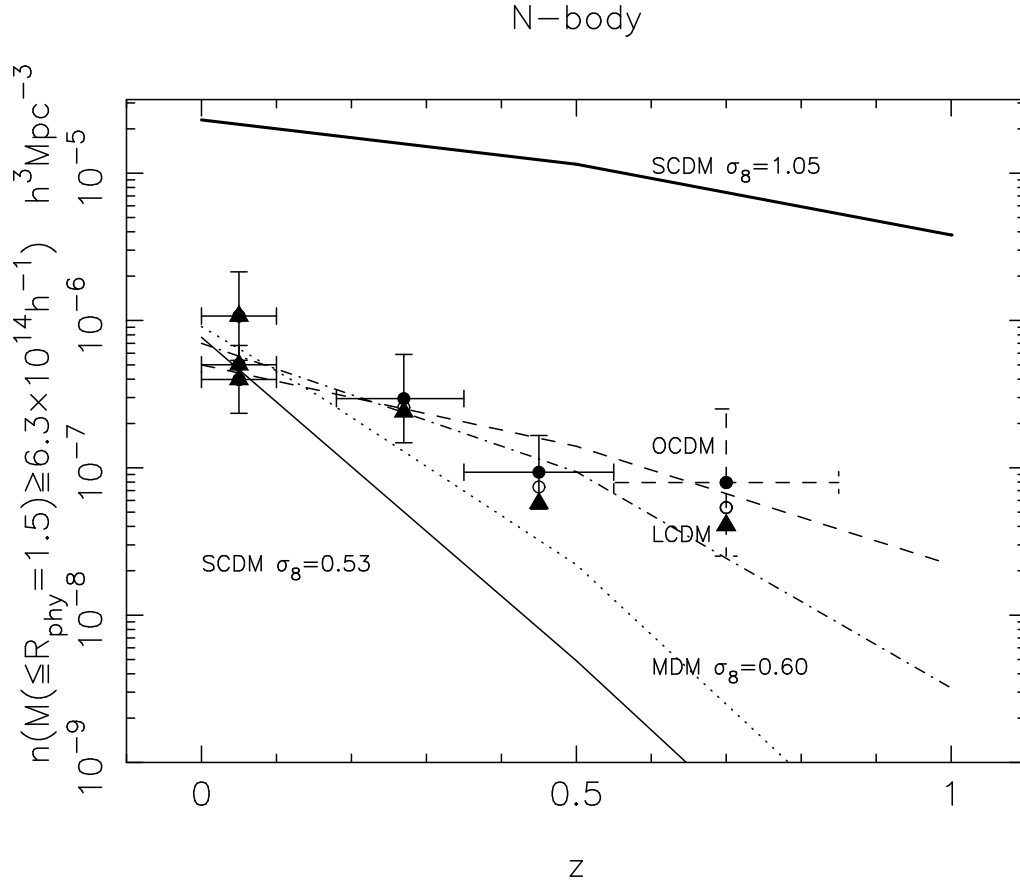


Fig. 2 The evolution of cluster abundance with redshift for massive, coma-like clusters ($M_{1.5} \geq 6.3 \times 10^{14} h^{-1} M_{\odot}$). The lines represent model predictions; the data points are from the CNOC survey. From Bahcall, Fan and Cen (1997) (updated fig.).

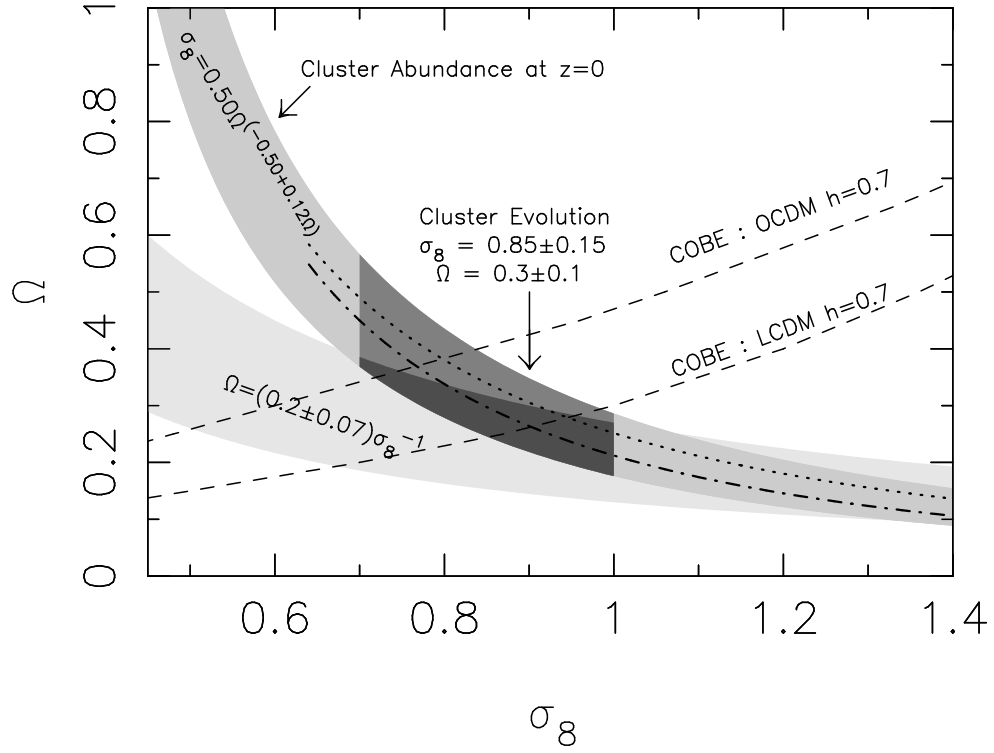


Fig. 3 Constraints placed on Ω and σ_8 by the cluster evolution data of Fig. 2 (dark region). Other bands indicate the present-day cluster abundance and the cluster dynamics (Fig. 1) constraints. From Bahcall, Fan and Cen (1997)